FIRST OPERATION OF THE ABORT GAP MONITORS FOR LHC*

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Abstract

The Large Hadron Collider (LHC) beam-dump system relies on extraction kickers that need 3 microseconds to rise to their nominal field. Since particles transiting the kickers during the rise will not be dumped properly, the proton population in this interval must always remain below quench and damage limits. A specific monitor to measure the particle population of this gap has been designed based on the detection of synchrotron radiation using a gated photomultiplier. Since the quench and damage limits change with the beam energy, the acceptable population in the abort gap and the settings of the monitor must adapt accordingly. This paper presents the design of the monitor, the calibration procedure and the detector performance with beam.

INTRODUCTION

The nominal LHC beam represents an unprecedented stored energy of 350 MJ, contained in 2808 bunches with a beam sigma of the order of 0.3mm. The extremely high destructive power of such a beam imposes an external dump [1], where the beam must be extracted completely from the LHC, diluted to reduce the peak energy density and then absorbed in a dedicated system. The LHC beam dumping system is located in Point 6 (see Fig. 1). A gap of 3μs in the circulating bunch pattern is present to allow the horizontally deflecting extraction kickers (MKD) to rise up to their nominal field.

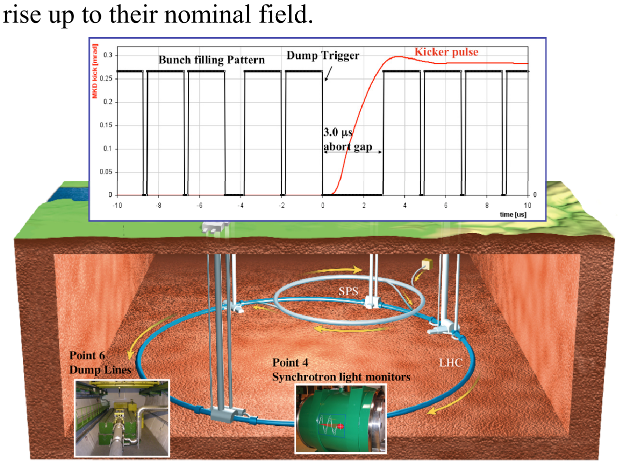

Figure 1: The LHC Beam Dumping system and the Abort gap monitoring system

The particles crossing the kickers during this rise time will not be dumped properly and will presumably be lost in the extraction region. Therefore the proton population present in the abort gap must remain below quench and damage limits under any circumstances. Monte-Carlo simulations using Geant4 were performed in order to estimate the proton population per bin of 100ns at quench threshold [2]. Since the quench and damage limits change with the beam energy, the acceptable population in the abort gap and the settings of the monitor must be adapted accordingly. Their predictions are displayed in Figure 2. The initial specification [3], shown in red, was done during the early construction phase of the machine, and more precise models were recently proposed based on the experience gained with first beam measurements and real quenches. The most relevant scenario in the case of a failure of the dumping system is to loose the beam in the vicinity of the superconducting quadrupole Q4, for which the quench threshold predictions are displayed in green in Fig. 2.

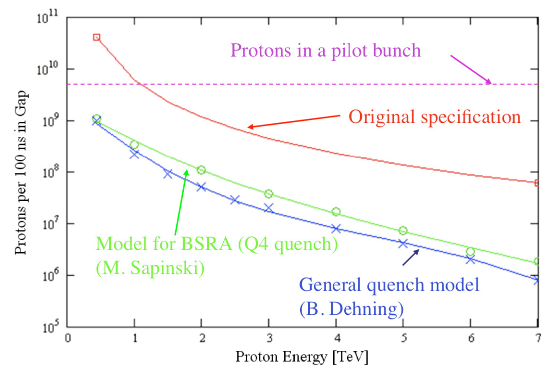

Figure 2: Quench threshold predictions as a function of the beam energy

A specific monitor has been designed to measure the particle population in this gap. The monitor is located in Point 4 (see Fig. 1) and is based on the detection of Synchrotron Radiation using a gated photomultiplier. This paper presents the design of the abort gap monitor and shows its performance during the first steps of beam commissioning.

ABORT GAP MONITORING

In LHC, Synchrotron Radiation monitors (BSRT) [4, 5] have been designed and installed to provide both transverse [6] and longitudinal [7] beam profiles measurements. The abort gap monitors (BSRA) are installed inside the BSRT telescope located just underneath the beam line, as depicted in Figure 3.

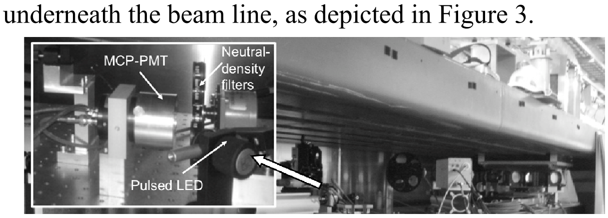

Figure 3: Picture of the Abort Gap Monitor inside the synchrotron light monitor telescope

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An optical beam splitter installed after the first focussing mirror reflects 90% for the imaging system and transmits the rest for the BSRA. A gated photomultiplier (PMT) is placed at the intermediate focal plane, since the diameter of the light there easily fits the 10-mm diameter photocathode. The PMT (Hamamatsu R5916-50) uses a micro-channel plate rather than dynodes. The gate allows it to sensitively detect the small gap signal without saturating from the large population elsewhere. The PMT output is then sent over 100m of coaxial cable to an adjacent technical gallery (US45) where the radiation levels are expected to remain negligible. It is continuously monitored by an IBMS charge-integrating board [8], using 2 integrators working in alternation, either integrating or sampling and digitizing. The IBMS board is installed as a mezzanine card on FPGA based VME board (DAB64x) [9].

The PMT has two important operating restrictions; a maximum duty cycle of 1% and a maximum time-averaged anode current of 100nA. To overcome these limitations, the gate is opened for the full 3-µs gap on every fourth turn (356 µs), for a duty cycle of 0.84% and a maximum output of 12 µA during the gate. The PMT gain must be adjusted with beam energy to track the light received from each proton.

Ideally, a particle population at the threshold should give a full-scale signal on the integrator (60 pC), allowing good measurements of populations below threshold. However, the maximum of 12 µA integrates over a 100-ns bin to only 1.2 pC. An amplifier with a voltage gain of over 50 is necessary to compensate for cable loss. The Hamamatsu C5594, with a voltage gain of 63 (36 dB), was purchased for this purpose.

The abort-gap measurement is updated every 100ms. During this time the signal of each of the 30 100ns slots of the abort gap is averaged inside the DAB64x's FPGA. At the same time the FPGA calculates, using digital filters, the mean and the standard deviation of the signal of each of these slots, which give the figure of merit of measurement. The effect of the AC coupling introduced by the C5594 amplifier is eliminated using a digital filter implemented in the front-end software (FESA).

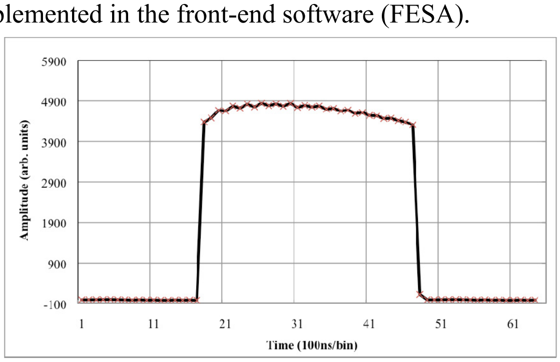

Figure 4: Calibration with a pulsed LED

A pulsed LED, visible in Fig. 3, has been installed close to the PMT and is used to check the system performance, like the linearity of integration over the entire gap. The LED is controlled directly by the DAB64x and can be gated down to 25ns. An example of the LED pulse is displayed in Figure 4, and in this case, the gate length was as long as the abort gap. This raw signal is used to adjust the digital filter compensating for the amplifier's AC coupling and to equalize the gain of the two integrators.

PERFORMANCES WITH BEAM

An example of the signal measured with the abort gap monitor is shown on Figure 5, as displayed in the control room using the expert Graphical User Interface. There were in this particular case two bunches separated by 3µs and sitting respectively on the RF bucket 1 and 1201 (one RF bucket being 2.5ns long). The trigger of the PMT was modified on purpose to observe them, the real abort gap being the 3 µs time interval just before bucket 1. Each dot on the plot corresponds to a 100ns integration time. Since a bunch is shorter than a nanosecond, it appears as a single point. The white zone displays the 3-µs gap, when the PMT is gated on. The grey zone gives an indication of the noise level on the electronics when the PMT is off.

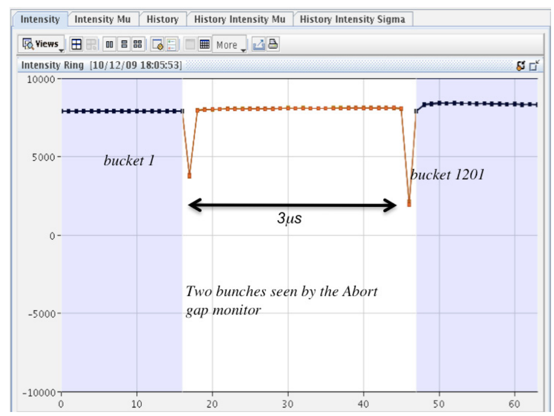

Figure 5: Two bunches seen by the abort gap at 450GeV

The BSRA calibration procedure relies on a direct comparison of the beam intensity measured by fast Beam Current Transformers and the Synchrotron light intensity measured by the PMT from a single bunch circulating in the machine. The light is heavily attenuated with neutral-density filters to match that from a quench-threshold population.

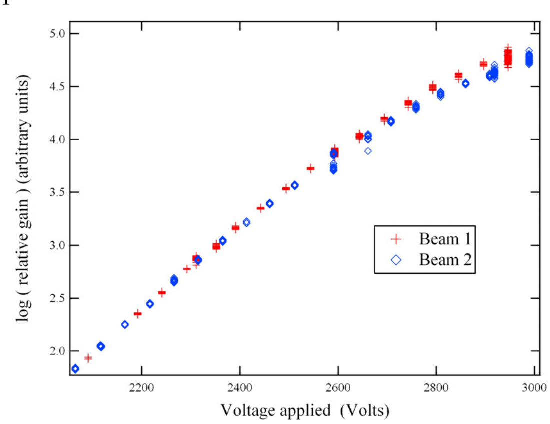

Figure 6: Calibration of PMT gain curve with beams

The amplitude of the BSRA signal strongly depends on the voltage applied to the PMT, which has a maximum value of 3300volts. A typical PMT gain curve measured with a pilot bunch (5.10^9 protons) at 450GeV is shown in Figure 6. The signal amplitude grows exponentially with the voltage and starts to saturate for higher values as expected by the manufacturer.

In LHC, the synchrotron light production relies on different sources [4]; a superconducting undulator [10] for low beam energies, a superconducting dipole for beam energies higher than 1.5TeV. The light intensity collected by the telescope changes both in intensity and spectrum as the beam energy is ramped up. A preliminary comparison between measurements and predictions performed using the simulation code SRW [11] are displayed in Fig. 7. The analysis is still ongoing and the simulations did not take into account neither the measured magnetic field maps nor the spectral response of the PMT photocathode. Nevertheless there is a good agreement between simulation and measured data. The biggest deviations can be observed in the energy range around 1TeV, where the spectrum of the undulator is shifted towards UV and the visible light from the dipole edge is just rising.

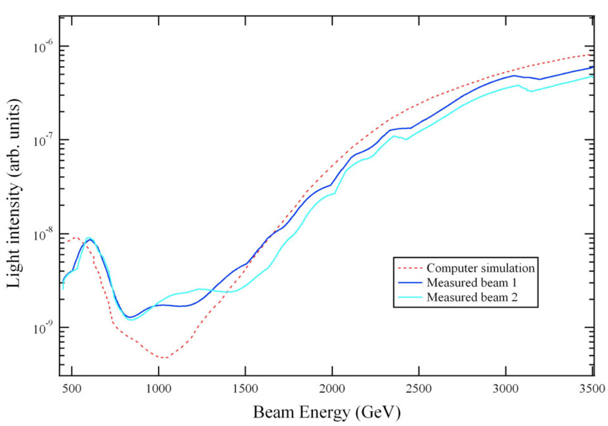

Figure 7: Evolution of the Synchrotron light intensity with beam energy

The sensitivity of the BSRA is found very good with respect to the specifications (see Fig. 2). It is providing measurements of the gap population at the level of $1/10^{th}$ of protons intensity at quench threshold (for almost any beam energies) with a signal to noise ratio better than 10. The main limitation to further improvement is linked to the presence of parasitic light in the telescope that starts to be visible for PMT voltages above 3000volts.

AUTOMATIC OPERATION

The monitoring of the abort gap is a critical measurement impacting on the safety of the machine. The monitor must operate automatically publishing the number of protons sitting in the abort gap with the best accuracy under all circumstances. The FESA performs the conversion from ADC counts to number of particles every 1ms. The conversion factor is calculated starting from a table that relates the emitted light to the particle energy based on our previous calibration. This table also contains the voltage that needs to be set on the PMT in order to keep optimal performance during the ramp. Depending on the amount of protons measured in the gap, a software alarm is sent that would trigger Radio-Frequency dampers [12], which would clean the abort gap to acceptable levels, before the beam is dumped.

OUTLOOK

Dumping the beam in LHC relies on a complex system, which must work with high reliability. The survey of the particle population in the abort gap is of prime importance at all times.

Abort Gap Monitors have been designed, installed and recently commissioned with beams. Their performance already enables to measure very low beam intensities with a good accuracy. Nevertheless, the system still needs further investigations before it operates automatically as expected.

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